TRAVELTIME AND LONGITUDINAL DISPERSION AT STEADY AND UNSTEADY FLOWS, COLORADO RIVER, GLEN CANYON DAM TO LAKE MEAD

U.S. Geological Survey

Open-File Report 92-____

Prepared in cooperation with the

U.S. BUREAU OF RECLAMATION

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CONVERSION FACTORS

Multiply metric unit	*By*	*To obtain inch-pound unit*
meter (m)	3.281	foot
cubic meter per second (m³/s)	35.31	cubic foot per second
kilometer (km)	0.6214	mile
kilogram (kg)	2.205	pound

TRAVELTIME AND LONGITUDINAL DISPERSION AT STEADY AND UNSTEADY FLOWS, COLORADO RIVER, GLEN CANYON DAM TO LAKE MEAD

By
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ABSTRACT

The effect of channel geometry and unsteadiness of flow on traveltime and longitudinal dispersion of flow in the Colorado River in Glen and Grand Canyons was evaluated in 1989 and 1991 by injecting a fluorescent dye and sampling for dye concentration at selected sites downstream. Measurements of a 26-kilometer reach of Glen Canyon, just below Glen Canyon Dam, were made at nearly steady discharges of 139, 425, and 651 cubic meters per second. A 380-kilometer reach of Grand Canyon was measured at a steady flow of 425 cubic meters per second and an unsteady flow with a daily mean discharge of about 425 cubic meters per second. In Glen Canyon, flow velocity through the study reach increased directly with discharge, but dispersion was much greater at the lowest of the three flows measured than at the higher two flows. Increased dispersion at low flow is thought to be caused by the emergence of cobble bars. In Grand Canyon, flow velocity varied slightly from reach to reach at both steady and unsteady flow but was not significantly different at steady and unsteady flow over the entire study reach. Also, longitudinal dispersion was not significantly different during steady and unsteady flow. The rate of longitudinal dispersion, as measured by rate of decrease in peak concentration and of increase in dye-cloud variance and traveling at a site, agrees with that predicted by one-dimensional theory, much more closely than is commonly found in rivers. Long tails on the time-concentration curves at a site, characteristic of most rivers but not predicted by the one-dimensional theory, were not found in this study. Absence of tails shows that, at the measured flow, the eddies that are characteristic of the study reach do not trap water for a significant length of time.

INTRODUCTION

Measurements of traveltime and longitudinal dispersion of flow in the Colorado River below Glen Canyon Dam (fig. 1) were made in October 1989 and May 1991 to evaluate the effects of channel geometry and unsteadiness of flow on these fundamental flow characteristics. The measurements are a key part of a program of data collection to support the development of physically based flow and transport models of the river. Data collection and model development are a part of an interagency, interdisciplinary study, the Glen Canyon Environmental Studies (GCES), coordinated by the U.S. Bureau of Reclamation (USBR). Flow and transport models are important to the GCES because assessment of effects of dam operations on all other components of the riparian environment depend on the ability to predict river stage and fluid and sediment transport that result from specified flow releases. Information from this and other GCES research will be incorporated into an Environmental Impact Statement (EIS) on dam operations ordered by the Department of the Interior.

Typically, water is released from Glen Canyon Dam in response to power demand, and resulting releases are very unsteady. As a part of ongoing environmental studies, Western Area Power Administration (Department of Energy) and the USBR have released water in such a way as to provide opportunities for data collection that would not otherwise be possible. In October 1989, a steady discharge of 142 m³/s was released for a period of 4 days to provide researchers the opportunity to study low flows. A traveltime and dispersion measurement of the reach from Glen Canyon Dam to Lees Ferry (fig. 1) was made during that steady-release

Figure 1.--Study area and location of dye-sampling sites.

period. Later, researchers and managing agencies agreed to release water

to provide a series of "research flows" over a period of about a year,

from July 1990 through July 1991. Each research flow was an 11-day period

during which the researchers specified the hourly releases. Research

flows were designed to provide opportunities to make measurements under

known and controlled conditions. Two research flows in May 1991 were

selected for the traveltime and dispersion measurements because (1) these

flows allowed evaluation of the difference in fluid transport during

steady and unsteady releases, which is a prime goal of GCES; (2) these

flows were the set of paired steady and unsteady releases with the highest

mean discharge, and high flows are most significant for sediment

transport; (3) a dense network of stage gages was available to provide

detailed information on stage changes throughout the reach during the

unsteady flow; and (4) suspended-sediment concentrations were expected to

be lowest in May, giving less chance of dye loss through adherence to

sediment.

Background

Channel geometry of the 406-kilometer study reach is variable and is controlled by bedrock geology to a large degree. Dye sampling sites (fig. 1 and table 1) were selected to define reaches of major differences in geology related to differences in channel slope, width, and depth. Measured reaches range from narrow bedrock channels characterized by rapids and pools typically 15 meters deep or more to wide, shallow channels with large midchannel gravel bars. Geometry of the channel is not well quantified, but some comparison of reaches can be made from sonic depthsounder records of a longitudinal profile and of 200 cross sections made in 1984 (Wilson, 1986). Widths, depths, and areas determined for measured reaches from the 200 cross sections (table 2) were computed by averaging values for cross sections in the specified reach. Cross sections were measured at locations at which it was feasible to manuever a motorized raft across the channel, and so locations are biased toward the pool rather than rapid sections. Channel constrictions formed by tributary debris fans, bedrock projections, or talus cause flow separation and eddy zones in all measured reaches. Transfer of water and sediment between the main downstream flow and the eddies is of major concern, because eddies are depositional sites for sand.

A mass of water marked by a tracer dye will move with the mean flow of the stream and mix with surrounding water to form a cloud of increasing size. In rivers, that mixing, called dispersion, is caused primarily by turbulent diffusion and velocity gradients (Fischer, 1973). A one-dimensional diffusion equation, in which flux is directly related to a concentration gradient by a diffusion coefficient, is commonly used to describe longitudinal dispersion—spreading of a mass of water in a

Table 1.--<u>Injection and sampling sites for traveltime measurements</u>

Site type	Distance from dam, in kilometers	River mile	Site name
	Glen Canyon reach, 1989		
Injection	0.0	-16.0	Glen Canyon Dam
Sampling	1.5	-15.2	Glen Canyon gage
Sampling	25.9	.0	Lees Ferry gage
	Glen Canyon reach, 1991		
Injection	0.3	-15.9	Below Highway 89 bridge
Sampling	25.9	.0	Lees Ferry gage
	Grand Canyon reach, 1991		
Injection	24.5	0.0	Lees Ferry Gage
Sampling	82.2	35.9	Nautiloid Canyon
Sampling	122.8	61.1	Gage above Little Colorado River
Sampling	147.7	75.8	Below Nevill's Rapid
Sampling	213.8	117.7	Mile 118 Camp
Sampling	292.4	166.5	National Canyon Gage
Sampling	368.1	213.6	Pumpkin Springs
Sampling	405.0	236.0	Gneiss Canyon

Two different distances below GCD for Lees Ferry gage.

Table 2.--<u>Characteristics of reaches defined by dye-sampling sites</u>

[Determined from surveyed cross sections at about 1.6-kilometer intervals
    at 680 cubic meters per second. Reach 1, dam to Lees Ferry; 2, Lees
    Ferry to Nautiloid Canyon; 3, Nautiloid to gage above the Little
    Colorado River; 4, Little Colorado gage to Nevill's Rapid; 5, Nevill's
    Rapid to Mile 118 Camp; 6, Mile 118 Camp to National Canyon; 7,
    National Canyon to Pumpkin Springs; 8, Pumpkin Springs to Gneiss
    Canyon]

Reach	Length, in kilo- meters	Bed slope	Width, in meters	Depth, in meters	Ratio of width to depth, in meters	Area, in square meters
1	24.5	0.00038	99.1	---	----	---
2	57.7	.00141	71.6	8.2	8.7	573
3	40.6	.00126	106.1	6.1	17.4	642
4	24.9	.00274	119.2	5.2	22.9	613
5	66.1	.00195	59.1	8.8	6.7	517
6	78.6	.00151	63.4	7.6	8.3	468
7	75.7	.00134	94.2	6.7	14.1	609
8	36.9	.00161	71.6	9.1	7.9	661

w/d ratio is unitless.

stream direction—in rivers (Fischer, 1973). According to that theory, the distribution of dye concentration with time at a point downstream from the point at which the dye has become mixed throughout the width and depth of flow will be positively skewed. Variance of the concentration distributions will increase linearly with time, and peak concentration will decrease as the square root of traveltime of the peak concentration (Nordin and Sabol, 1974). A number of studies have shown that the one-dimensional theory does not adequately describe longitudinal dispersion in many rivers (Nordin and Sabol, 1974; Day, 1975; Godfrey and Frederick, 1970; Seo, 1990). Typically, concentration distributions in rivers are more positively skewed, variance of the distribution increases at a greater rate than predicted by the one-dimensional theory. Also, measured distributions have long tails not predicted by the one-dimensional theory. Tails generally are attributed to temporary storage in zones of slowly moving or stagnant water along the channel bed and banks, and much of the effort to develop models of longitudinal dispersion has centered on incorporation of those "dead zones" (Bencala and Walters, 1983; Seo, 1990; Valentine and Wood, 1977).

Purpose and Scope

The purposes of the study were to determine traveltime and longitudinal dispersion characteristics for distinctive subreaches of the study reach at steady flow and to evaluate the effect of unsteady flow on traveltime and dispersion. Data will be used with stage, channel-geometry, and bed-material information to develop a physically based, unsteady-flow model for the study reach. The traveltime measurements will be used to verify the ability of that model to transport the fluid mass. This report presents a preliminary analysis of the data, a discussion of the implication of the results to transport under flow alternatives presented in the Glen Canyon Dam EIS, and a statement of the status of the work.

Acknowledgments

Randy Fabres designed the method of dye injection for the Grand Canyon measurements and piloted the boat during the injection. Tim Deutschlander and Randy Fabres were the boatmen during the Grand Canyon measurements, and their skill and dedication to the goals made it possible to outrun the dye and collect needed samples. Denise Hogan, K.C. Deutschlander, and Monte Becker provided many tasty and nourishing meals under considerable time pressures and difficult conditions. Bernice Cobb and Dan Lunsford volunteered their time to help in the sampling. These measurements could not have been made successfully without the enthusiastic participation of these and the U.S. Geological Survey crew members.

Approach

Measurements were made by injecting rhodamine WT, a red fluorescent dye developed as a water tracer, into the river and collecting water samples during passage of the dye past selected sites downstream from the injection. When possible, sampling began before the arrival of the dye at a site and continued until concentration had reached background values.

The measurement in October 1989 consisted of one injection at Glen Canyon Dam, and sampling at two gaging stations downstream (fig. 1 and table 1). Each May 1991 measurement consisted of two injections—an injection of dye from a point just downstream from the dam and sampling at the Lees Ferry gaging station (the Glen Canyon reach) and a separate injection at the Lees Ferry gage and sampling at locations downstream from Lees Ferry (the Grand Canyon reach) (table 1). Sample sites were selected to define reaches with significantly different geometry (table 2). The 11 subreaches defined by Schmidt and Graf (1990, table 2, p. 55) were the basis for site selection, but some of the shorter reaches with small differences in geometry were combined to give reaches for the traveltime measurements that were feasible to sample.

For the Glen Canyon reach, the traveltime of dye through the reach was expected to be less than a full daily hydrograph, and it was decided to measure the traveltime at the peak discharge of the unsteady flow (651 m³/s on May 8, 1991). The reach was also measured during the steady 425 m³/s flow in May 1991. These measurements, together with the measurement made in October 1989 at about 140 m³/s, give information on traveltime and dispersion at steady flow over much of the powerplant operation range of about 28 to 785 m³/s. For the Grand Canyon reach, the two May 1991 measurements give information for steady and unsteady flows with about the same daily mean discharge. Discharge at Lees Ferry during the steady-flow measurement, May 20-25, 1991, was 425 m³/s and during the unsteady-flow measurement, May 6-11, 1991, ranged from 92 to 754 m³/s with a mean of 428 m³/s (fig. 2).

Figure 2.--Discharge for the unsteady-flow traveltime measurement at the gaging station, Colorado River at Lees Ferry, Arizona.

METHODS

Established techniques for estimation of dye dosage, sampling, and laboratory analysis of dye samples were used in this study (Wilson and others, 1986; Kilpatrick and Wilson, 1989). Dye dosage was computed using methods presented by Kilpatrick and Wilson (1989, p. 14-15) using an estimated traveltime of the peak concentration. For the Grand Canyon reach, a dosage of 635 kg of the 20-percent stock solution (127 kg of dye) was estimated to give a peak of about 2 μg/L at the end of the reach for the lowest expected velocity, and that amount was injected in the first measurement. Very low dispersion rates kept peak concentrations higher than estimated during that measurement, and half the amount of

dye—63.5 kg —was injected for the second measurement. For the Glen Canyon reach, a dosage of 21.5 kg of dye was used for the 1989 measurement and 9.1 kg of dye was used for both 1991 measurements.

Dye was injected over a period of a few minutes in a line across the central part of the cross section. For the 1989 Glen Canyon reach measurement, dye was divided into four equal parts and poured into the river from the transformer deck of the dam from locations on either side of the two generator outlets that were releasing water at the time. The injection took a total of 7 minutes. Samples were collected from the center of flow from cableways at the gaging stations Colorado River below Glen Canyon Dam (09379910) and Colorado River at Lees Ferry (09380000) (fig. 1 and table 1). For the 1991 Glen Canyon reach measurements, dye was poured from a boat as the boat moved across the center part of a cross section of the channel just downstream from the dam. Near-surface dip samples were collected with a hand sampler from three points across the channel from a boat under the cableway at the Lees Ferry gage.

For the Grand Canyon reach, dye was poured from a raft as the raft passed through the center two-thirds of the flow in the cableway section at Lees Ferry. Each injection took about 5 minutes. For sampling, two rafts moved crews from site to site downstream from Lees Ferry. The rafts moved and camped independently, allowing the crews to "leapfrog" downstream, one staying at a sample site to sample the dye cloud, and the other moving ahead to the next site. In addition, two members of the crew were able to camp independently at a third site when it was judged to be advisable to occupy three sites at a time.

Most samples were collected by dipping a sample bottle just under the surface near the stream bank or tossing a bottle in a sample holder into the flow a short distance from the bank. Samples were collected in areas of downstream flow that were judged to be the most evenly distributed across the channel in the vicinity. Most sample sites were at riffles or rapids. An automatic sampler (Kilpatrick, 1972) was used to collect samples over much of the dye cloud at Pumpkin Springs (table 1).

Discharge at gaging stations was obtained from recorded stage and a stage-discharge relation. An unsteady flow-routing model is being calibrated with data from the gaging stations and stage data from a network of temporary gages. Stage record and rating curves were available for gaging stations Colorado River below Glen Canyon Dam (09379910); Colorado River at Lees Ferry (09380000); Colorado River above the Little Colorado River, near Desert View (09383100); Colorado River near Grand Canyon (09402500); Colorado River above National Canyon, near Supai (09404120); and Colorado River above Diamond Creek, near Peach Springs (09404200 and fig. 1). The network of temporary stage recorders provided stage information at about 8-kilometer intervals. In addition, stage

at sampling sites not near an existing gage was recorded during sampling at the unsteady-flow measurement with a portable gage that consisted of a submersible pressure transducer and datalogger.

Filter fluorometers were used to measure dye concentration in the field to permit adjustment of sampling interval and to ensure that sampling continued until dye was past the site. Samples were collected in glass vials that were capped tightly, packed in opaque boxes, and transferred to the Geological Survey laboratory in Tucson. A set of dye standards was prepared from the dye lot used in the measurements according to the methods described by Wilson and others (1986); the calibration of a Turner[1] Model 10 filter fluorometer was checked with the standards. Measurements of standards and samples were made under constant temperature conditions in the laboratory.

Background fluorescence was determined at most sites by measuring samples of water collected before arrival of the dye cloud. Background concentration was low—0.01 to 0.14 μg/L. Background concentration was subtracted from concentrations measured in the laboratory to give the concentration values used in this report.

The fraction of injected dye recovered at each sampling site during steady flow was computed to be above 0.9 (table 3). Errors in the computation include errors incurred in sample analysis, in comparison of the area under the time-concentration curves, and in discharge. Discharge

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[1]Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 3.--<u>Recovery ratios for dye at each sampling site for the</u>
<u>steady-flow measurement, May 20-25, 1991</u>

[Weight recovered was computed by multiplying the area under the time-
concentration curve by the discharge and by a constant factor to correct
the units. The correction factor is 0.08640 = 86,400 seconds per day
multiplied by 10^{-9} kilograms/microgram multiplied by 1,000 liters per cubic
meter. Recovery ratio was computed by dividing the weight recovered by 63.5
kilograms, which is the weight of dye injected]

Site	Area under curve, in microgram-days per liter	Discharge, in cubic meters per second	Weight recovered, in kilograms	Recovery ratio, dimensionless
Nautiloid Canyon	1.6300	425	59.9	0.94
Above the Little Colorado River	1.6358	425	60.1	.95
Below Nevill's Rapid	1.7011	430	63.2	1.00
Mile 118	1.6007	433	59.9	.94
National Canyon	1.5788	436	59.5	.94
Pumpkin Springs	1.5327	436	57.7	.91
Gneiss Canyon	1.5549	436	58.6	.92

values (table 3) were obtained from provisional stage record and rating curves at gaging stations and are likely to be revised when stage record and ratings are reviewed and updated (D.J. Bills, hydrologist, U.S. Geological Survey, oral commun., 1991). These errors account for the fact that the computation results in more dye recovered at the site below Nevill's Rapid than at the site upstream. The high recovery ratio is unusual—dye is known to be decomposed by sunlight and to adhere to sediment, and losses are commonly in the range of 30-50 percent (Hetling and O'Connell, 1966; Scott and others, 1969; Graf, 1986). Recovery ratios have not yet been computed for the unsteady-flow measurement, but initial estimates at two sites suggest that dye loss was significantly greater during unsteady flow. Greater loss may be attributed to stranding of dye in eddy zones when stage dropped. Because recovery ratios are very high and because discharge revisions may be significant, concentrations presented in this preliminary report have not been adjusted to account for dye losses.

Curves of dye concentration as a function of time at a sampling site were plotted, and the first three moments of the distributions were computed using numerical integration. The first moment, dye-cloud centroid, and the rate of travel of the centroid gives velocity through the measured reach. The second and third moments, variance and skewness, are measures of the dispersion, or spreading of the dye cloud.

RESULTS AND DISCUSSION

Glen Canyon Reach

Results of the Glen Canyon reach measurements show that flow velocity through the reach increases proportionally with discharge, but dispersion is proportionally much greater at the lowest flow than at the higher two flows measured (fig. 3 and table 4). Velocity increased from 0.3 to 1.0 m/s as discharge increased from 139 to 651 m³/s. The bed slope in the reach is lower than that in downstream reaches (table 2), and velocity at 425 m³/s is less than that of any of the downstream reaches at that discharge. Peak dye concentration was normalized by dividing by the weight of dye injected and multiplying by the discharge, giving a quantity called unit concentration (Kilpatrick and Taylor, 1986; Hubbard and others, 1982). Dye loss was insignificant during each measurement, and no adjustment of concentration for loss was required.

The changes in unit peak concentration, dye-cloud variance, and dye-cloud skewness with flow velocity all show that dispersion is much greater at the lowest flow than at the higher two flows (fig. 3). Duration of the dye cloud past Lees Ferry, measured from the time of arrival of the dye to the time when a concentration of 10 percent of the peak concentration was reached on the trailing edge of the dye cloud, is also proportionally much greater at the lowest flow than the two higher flows. Duration was 4.5 hours at 651 m³/s, 6.5 hours at 425 m³/s, and 12.3 hours at 139 m³/s. Quantitative measures of changes in spatial characteristics of flow are not available, but qualitative observation suggests that the increased dispersion at low flow results from a change in channel geometry and sinuosity caused by the emergence of large cobble bars and riffles.

Figure 3.--Relation of discharge, dye-cloud skewness, dye-cloud variance, and unit-peak concentration to reach velocity, Glen Canyon reach.

Table 4.--Statistics of the time-concentration curves, Glen Canyon, 1989 and 1991

Distance from injection, in kilometers	Discharge, in cubic meters per second	Maximum concentration, in micrograms per liter	Time, in hours		Time variance, in hours squared	Coefficient of skew, dimension-less	Reach velocity, in meters per second
			Centroid	Peak			
		Measurement, 1989					
1.5	144	61.2	1.35	1.12	0.115	1.238	....
25.9	139	5.78	21.8	20.2	10.4	1.225	0.33
		Steady-flow measurement, 1991					
25.6	425	2.27	9.84	9.70	1.34	.450	0.72
		Unsteady-flow measurement, 1991					
25.6	651	1.98	7.07	6.60	0.708	.560	1.0

Grand Canyon Reach

Dye was sampled at seven sites in the Grand Canyon reach during the measurement at steady flow (table 1 and fig. 4). Time-concentration curves at sample sites are unusual in that although the curves have a slight positive skew, they do not have the long tails that are typical of such curves in natural streams. Because of the absence of tails, it was feasible to sample the dye cloud until background concentration had been reached at most sites. Dye was sampled at six sites during the unsteady-flow measurement, but the leading edge of the dye-cloud was not sampled at several sites (fig. 5). The time-concentration curves for unsteady flow are similar to those for steady flow in that they do not have long tails, but the shapes of curves at individual sites appear to be strongly influenced by discharge changes in the reach as the dye passed. For example, the curve at Nautiloid Canyon for unsteady flow is much like that for steady flow. Discharge was nearly steady at the peak flow of the daily range during most of the time the dye traveled through the reach upstream from that site. However, the curve at the site below Nevill's Rapid has a high negative skewness because discharge was increasing in the reach above that site as the dye passed.

For the steady-flow measurement, velocity varied slightly from reach to reach. The lowest velocity (0.75 m/s) was measured in the reach between Nautiloid Canyon and the Little Colorado River confluence—the Lower Marble Canyon reach of Schmidt and Graf (1990, table 2, p. 55). The highest velocity (1.1 m/s) was measured between the Little Colorado River confluence and the site below Nevill's Rapid (Furnace Flats reach) and between Mile 118 Camp and Pumpkin Springs (Middle Granite and Muav

Figure 4.--Variation of dye concentration with time at sampling sites, steady-flow traveltime measurement, May 20-25, 1991.

Figure 5.--Variation in dye concentration with time at sampling sites, unsteady-flow traveltime measurement, May 6-11, 1991.

Gorges). Velocity was not significantly correlated with any of the channel geometry characteristics given in table 2. Velocity of flow in individual reaches during unsteady flow ranged from 0.67 m/s in the Lower Marble Canyon reach to 1.3 m/s in the reach between the site below Nevill's Rapid and the site at Mile 118 Camp (Granite Gorge). For unsteady flow, differences in velocity through individual reaches were more strongly influenced by discharge in the reach as the dye passed than by the geometry of the reach.

Traveltime of the dye-cloud centroid increased linearly with distance traveled for both steady and unsteady flow. Although velocity varied from reach to reach during both measurements, velocity differences were not great enough to significantly alter the traveltime-distance relation (fig. 6). Traveltime was slightly less during unsteady flow than during steady flow, but velocity over the entire measured reach was not significantly different—0.98 m/s for steady flow and 1.0 m/s for unsteady flow.

Downstream changes in peak concentration and dye-cloud variance and duration time are all measures of the longitudinal dispersion. For steady flow, peak concentration decreased as the square root of traveltime (fig. 7). Peak concentration was 12.5 μg/L at the first sampling site, 57.7 km downstream from the injection, and was 5.3 μg/L at the last site, 380 km from the injection. Nonlinear regression techniques were used to fit an equation of the form $C_m = aT_p^b$, where C_m is peak concentration and T_p is traveltime of the peak concentration, to the data.

Figure 6.--Relation of traveltime of the dye-cloud centroid to
distance traveled, Grand Canyon reach.

Figure 7.--Relation of peak concentration to distance traveled,
Grand Canyon reach.

Table 5.--<u>Statistics of the time-concentration curves for the steady-flow measurement.</u>
<u>Grand Canyon. May 20-25, 1991</u>

[Reach velocity was computed as velocity of the centroid of the time-concentration
curve]

Distance from injection, in kilometers	Discharge, in cubic meters per second	Peak concentration, in micrograms per liter	Time, in hours		Time variance, in hours squared	Coefficient of skew, dimensionless	Reach velocity, in meters per second
			Centroid	Peak			
57.7	425	12.5	18.5	18.4	1.48	1.161	0.87
98.3	425	8.34	33.5	33.1	4.16	.543	.75
123.2	430	8.33	39.9	39.3	4.49	.505	1.1
189.3	433	6.91	58.8	58.6	5.25	.290	.97
267.9	436	6.03	79.0	79.0	6.23	.251	1.1
343.6	436	5.34	98.4	98.3	8.10	.368	1.1
380.5	436	5.32	108.3	107.9	9.36	.253	1.0

Table 6.--<u>Statistics of the time-concentration curves for the unsteady-flow measurement, Grand Canyon, May 6-12, 1991</u>

[Discharge is the mean at the site for the period of passage of the dye cloud. Reach velocity was computed as velocity of the peak concentration]

Distance from injection, in kilometers	Discharge, in cubic meters per second	Peak concentration, in micrograms per liter	Time, in hours		Time variance, in hours squared	Coefficient of skew, dimensionless	Reach velocity, in meters per second
			Centroid	Peak			
57.7	362	18.1	14.3	13.8	1.60	0.805	1.1
98.3	336	13.4	31.2	32.3	9.31	-.111	.67
123.2	(¹)	10.9	38.0	39.0	6.35	-.526	1.0
189.3	(¹)	9.97	--	53.0	--	--	1.3
267.9	(¹)	9.74	--	76.5	--	--	.93
380.5	(¹)	8.11	103.6	101.7	14.3	.658	1.2

[1]NA, not yet available.

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An exponent of -0.50 was obtained. This is a much slower rate of decrease in peak concentration than is typical, but it is about the rate that would be expected if the one-dimensional mixing theory holds. Peak concentrations were higher during the unsteady-flow measurement because of the greater amount of dye injected, but rate of decrease was about the same as that for steady flow.

For steady flow, dye-cloud variance increased with distance traveled and with traveltime (fig. 8). The exponent of a equation of the form given above relating variance to traveltime of the peak concentration is 0.80, lower than any of the measured values presented in a summary of dispersion data by Nordin and Sabol (1974), and lower than that predicted by the one-dimensional theory. Variance increased with distance and traveltime during unsteady flow, but the increase was less systematic (fig. 8). Duration of the dye cloud, measured from the time of first arrival of the dye at the site to the time at which concentration returned to background, was 15.5 hours for steady flow and 17.5 hours for unsteady flow at the site 380 km downstream from the injection. For steady flow, duration increased with traveltime of the peak concentration according to the relation $T_d = 2.4\ T_p^{0.45}$, where T_d is dye-cloud duration in hours. The increase in dye-cloud duration is considerable slower than is typical (Graf, 1986; Kilpatrick and others, 1989).

For the steady-flow measurement, time-concentration curves at all sites were positively skewed (fig. 9). Skewness decreased with time and distance, and curves approach a normal distribution toward the

Figure 8.--Relation of dye-cloud variance to traveltime of the
dye-cloud centroid, Grand Canyon reach

Figure 9.--Relation of dye-cloud skewness to traveltime of
the dye-cloud centroid, Grand Canyon reach.

downstream end of the study reach. Skewness is higher for most sites during the unsteady-flow measurement and is positive or negative, depending on the way in which discharge changed during dye passage. Curves for sites in which the discharge increased in the reach upstream as the dye passed are negatively skewed, whereas those for which the discharge was steady or decreasing are positively skewed. None of the curves for the Grand Canyon reach have the long tails typical of most streams. For steady flow, skewness decreased linearly with traveltime of the peak concentration.

Implications for Flow Alternatives

Results suggest that unsteadiness of flow has little effect on flow velocity or dispersion at the relatively high mean discharge at which the Grand Canyon reach was measured in this study. Initial estimates of dye losses during steady and unsteady flow indicate that some water may be stranded by decreasing stage during unsteady flow. In the Glen Canyon reach, flow velocity varies directly with mean discharge, but dispersion is much greater at the lowest of the three measured flows than at the higher two flows. The increased dispersion apparently is caused by the emergence of large cobble bars at low flow (140 m³/s). Because similar changes in channel geometry occur in some individual reaches of the Grand Canyon study reach, the low dispersion measured in the Grand Canyon reach at steady and unsteady flow may not be indicative of dispersion during flow releases with a low mean discharge.

An unsteady flow-routing model developed by Jobson (1989) is being calibrated with data from the research flows and will be used to provide discharge during passage of the dye at sample sites during unsteady flow. Discharge estimates from the model will allow the computation of recovery ratios and conservation concentrations for the unsteady-flow measurement. Dye-transport data are being used to calibrate a solute-transport model (Jobson and Schoellhamer, 1987), and the calibrated flow model will also provide flow input to that model. Once calibrated with data from this study, the combined flow and transport models will permit estimation of flow velocity and dispersion

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characteristics through individual measured reaches for the specific flow
alternatives being considered in the Glen Canyon Dam EIS. Results of
model calibration and application to the EIS flow alternatives will be
included in an updated report.

CONCLUSIONS

The preliminary analysis of traveltime and dispersion data presented above support the following conclusions:

1. Change in peak concentration, dye-cloud variance, and dye-cloud duration with traveltime of the dye-cloud peak show that dispersion in the study reach is less than is commonly found in other rivers.

2. The data fit a simple one-dimensional mixing model, with no modifications to account for dead zones, much better than do most rivers for which measurements are available.

3. The absence of tails on the time-concentration curves shows that retention time of water in eddies is very short—these zones do not act as dead zones.

4. Differences from reach to reach in large-scale channel geometry and slope have a relatively small effect on flow velocity and dispersion.

5. Unsteadiness of flow affects the velocity through individual reaches, but velocity over the entire 380-kilometer Grand Canyon reach is not significantly different at steady and unsteady flow. Unsteadiness of flow does not appear to affect the rate of dispersion significantly.

6. Channel-geometry changes at low flow significantly increase the dispersion in the Glen Canyon reach and probably also increase the dispersion in at least some of the individual reaches in the Grand Canyon reach.

These conclusions will continue to be examined during the ongoing analysis.

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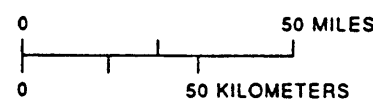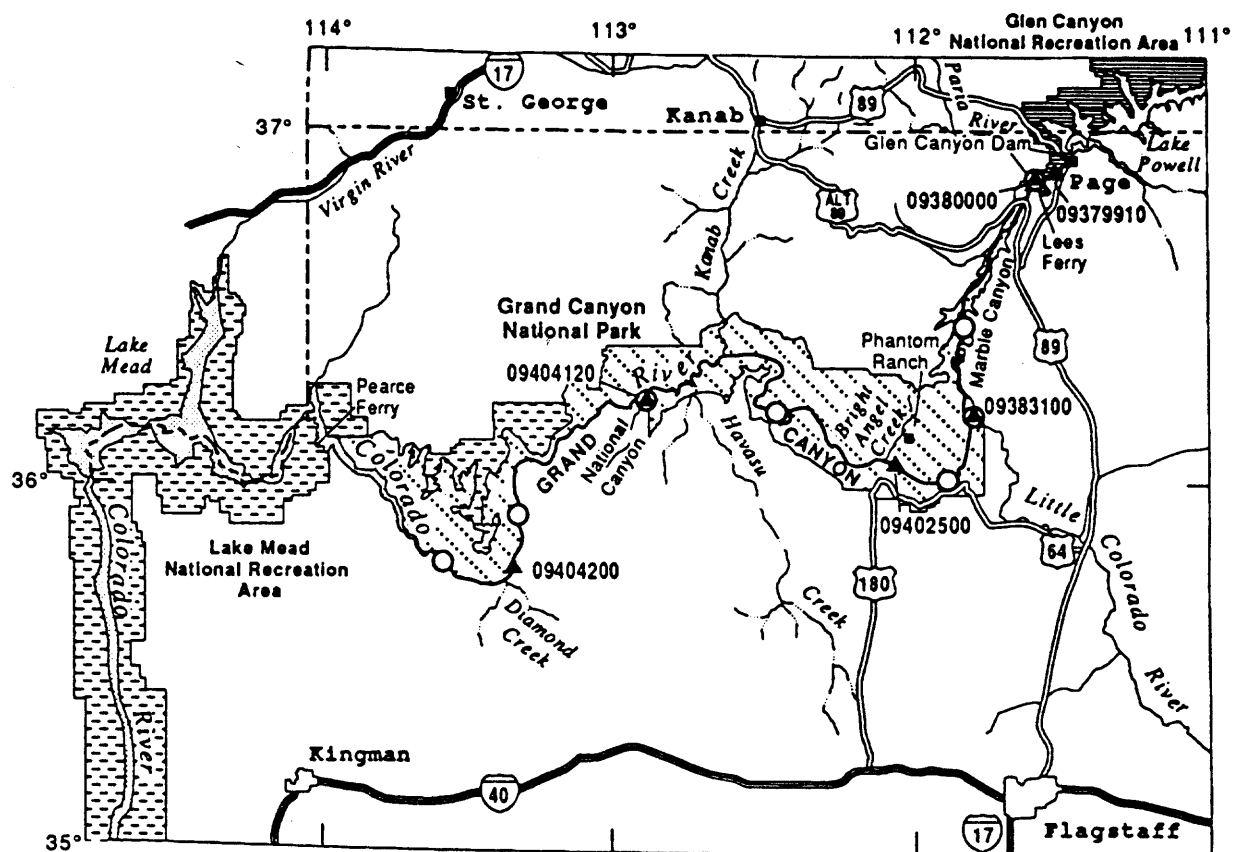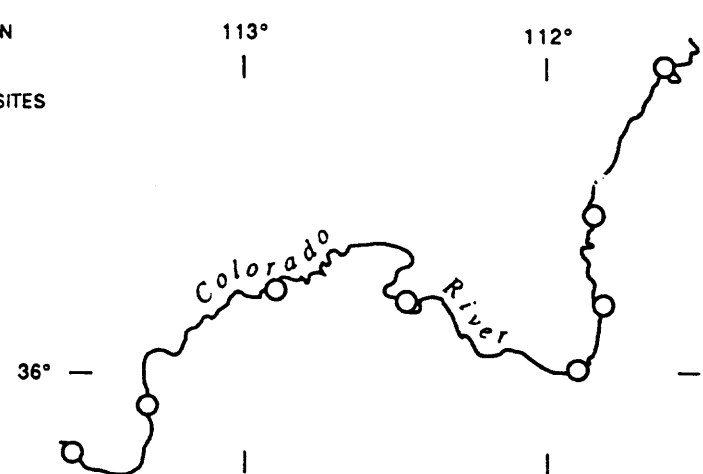
Figure 1.—Study area and location of
dye-sampling sites.

Figure 2.—Discharge for the unsteady flow traveltime measurement at the gaging station, Colorado River at Lees Ferry, Arizona.
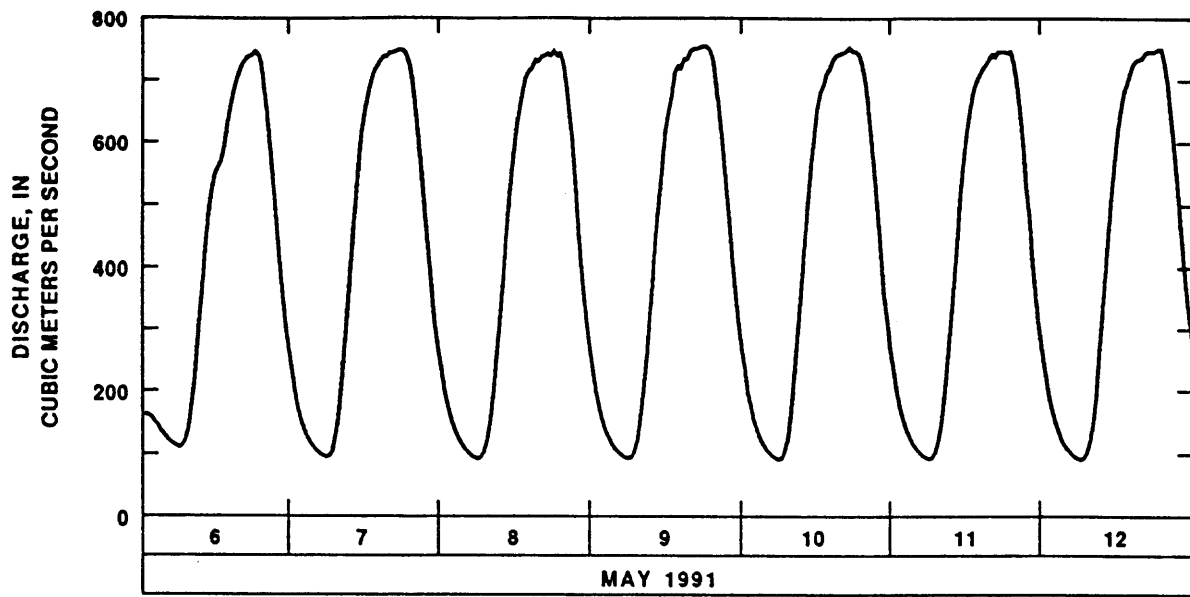
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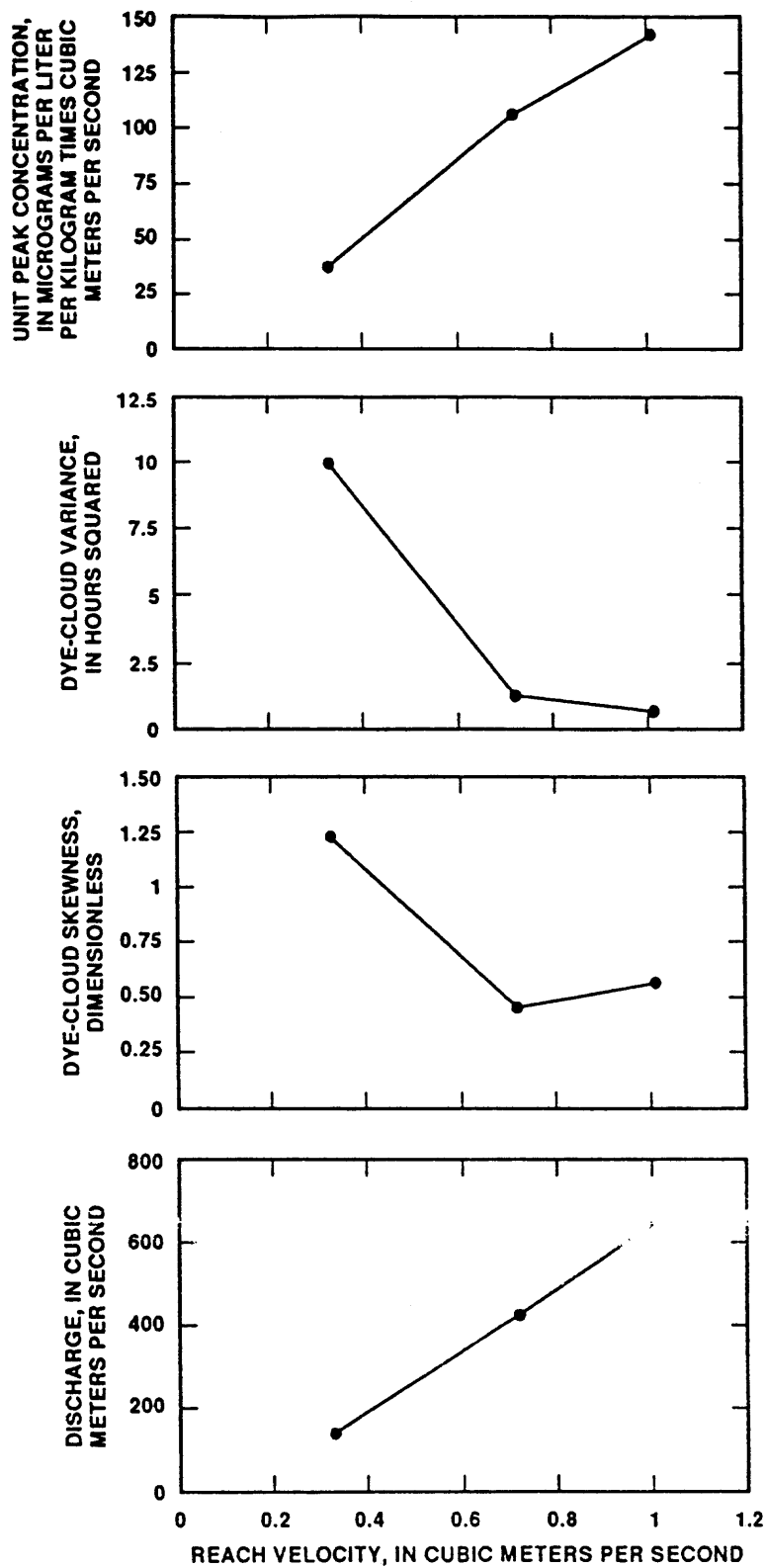
Figure 3.—Relation of discharge, dye-cloud skewness, dye-cloud variance,
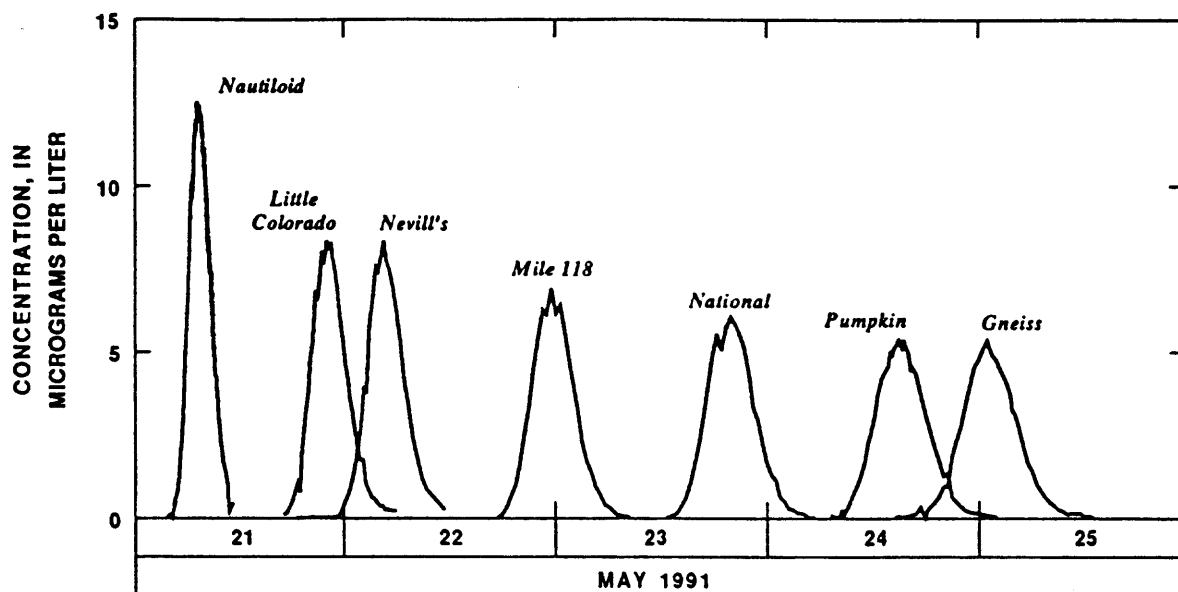and unit-peak concentration to reach velocity, Glen Canyon reach.

Figure 4.—Variation of dye concentration with time at sampling sites, steady-flow traveltime measurement, May 20-25, 1991.
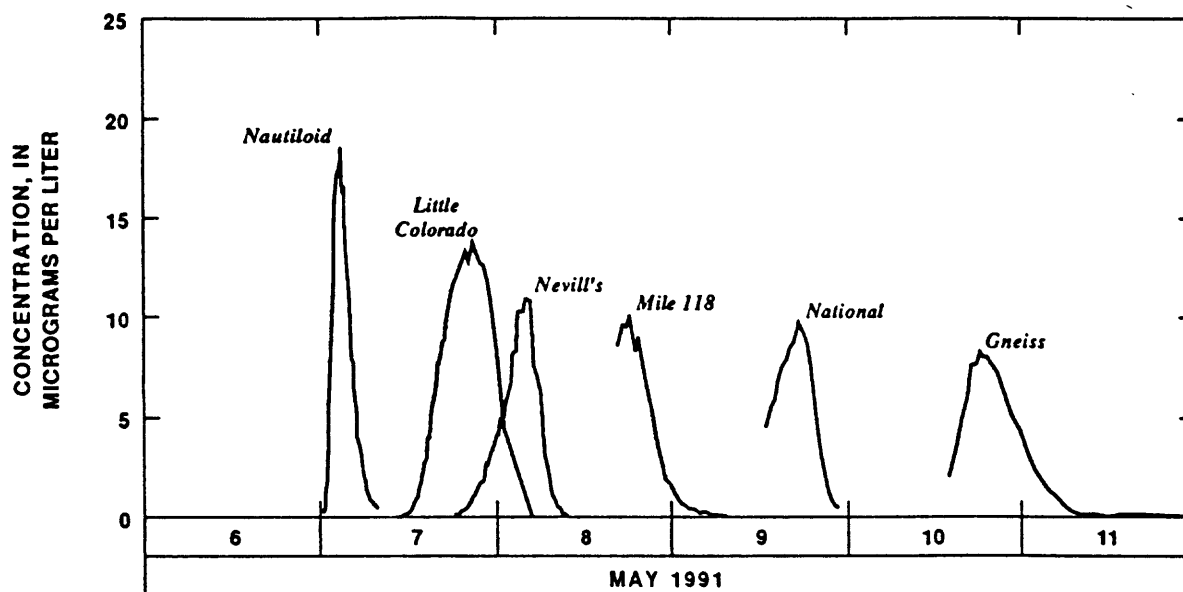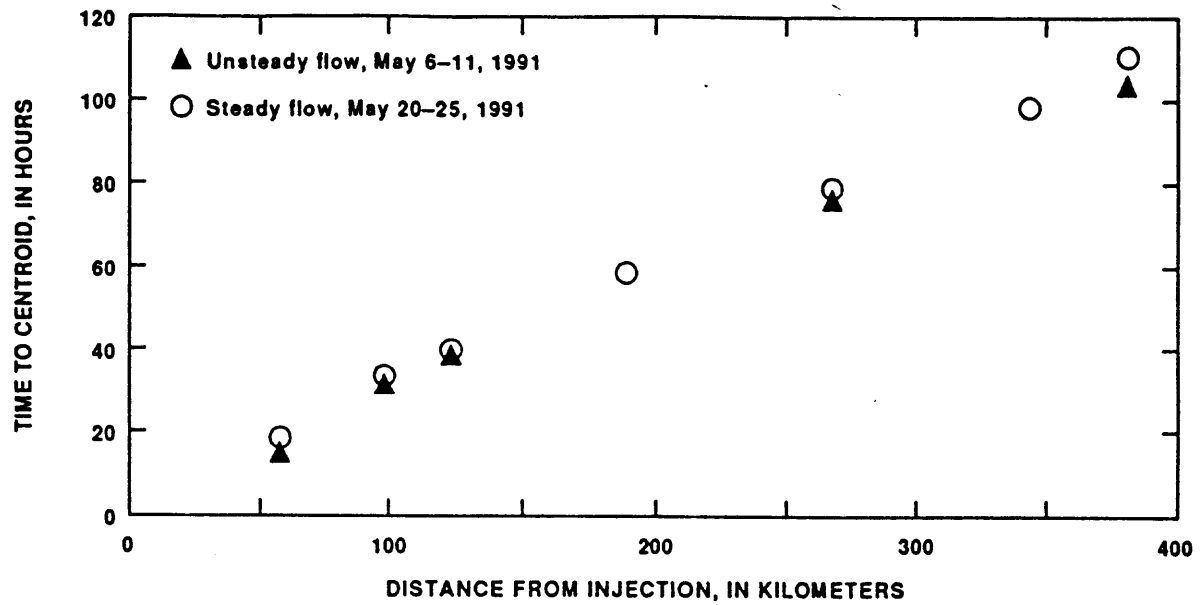
Figure 5.—Variation in dye concentration with time at sampling sites, unsteady-flow traveltime measurement, May 6-11, 1991.

Figure 6.—Relation of traveltime of the dye-cloud centroid
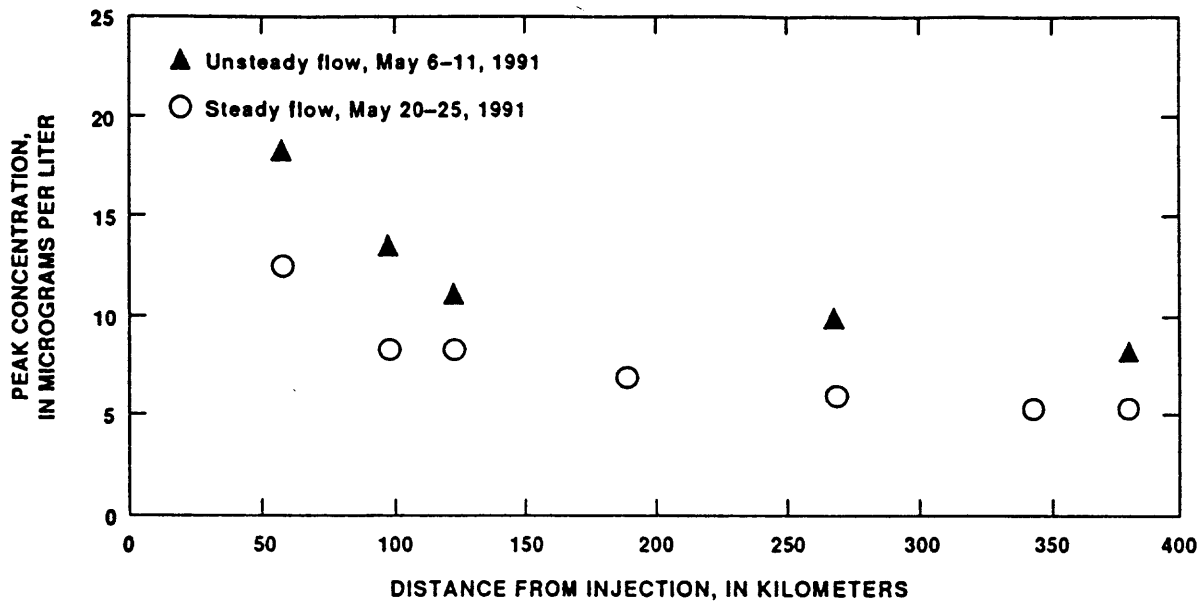to distance traveled, Grand Canyon reach.

Figure 7.—Relation of peak concentration to
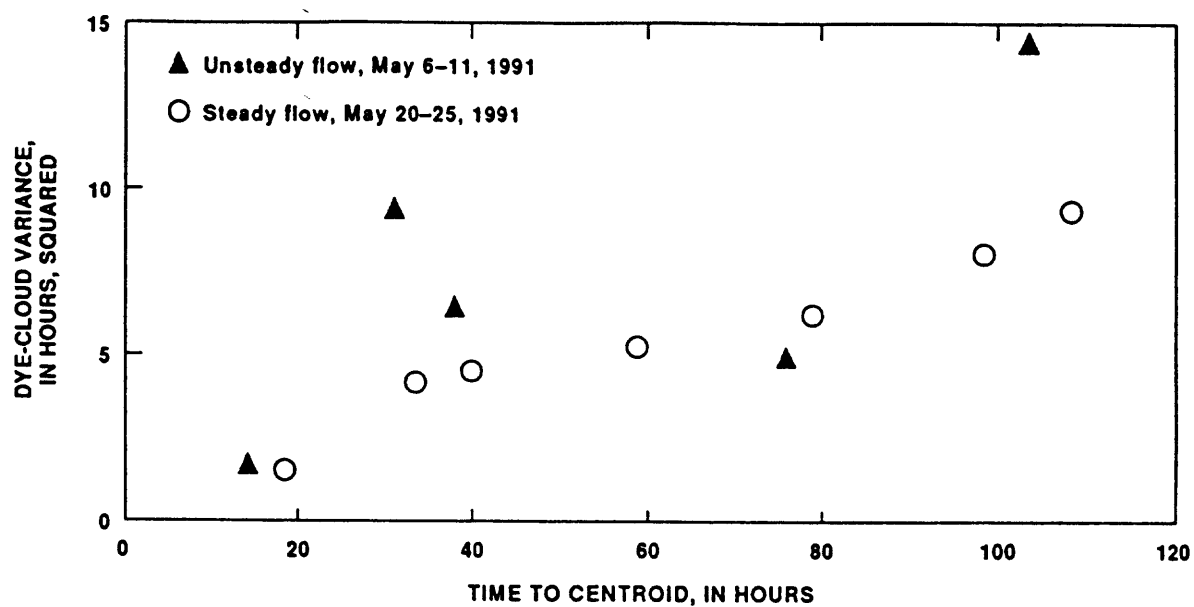distance traveled, Grand Canyon reach.

Figure 8.—Relation of dye-cloud variance to traveltime of the dye-cloud centroid, Grand Canyon reach.
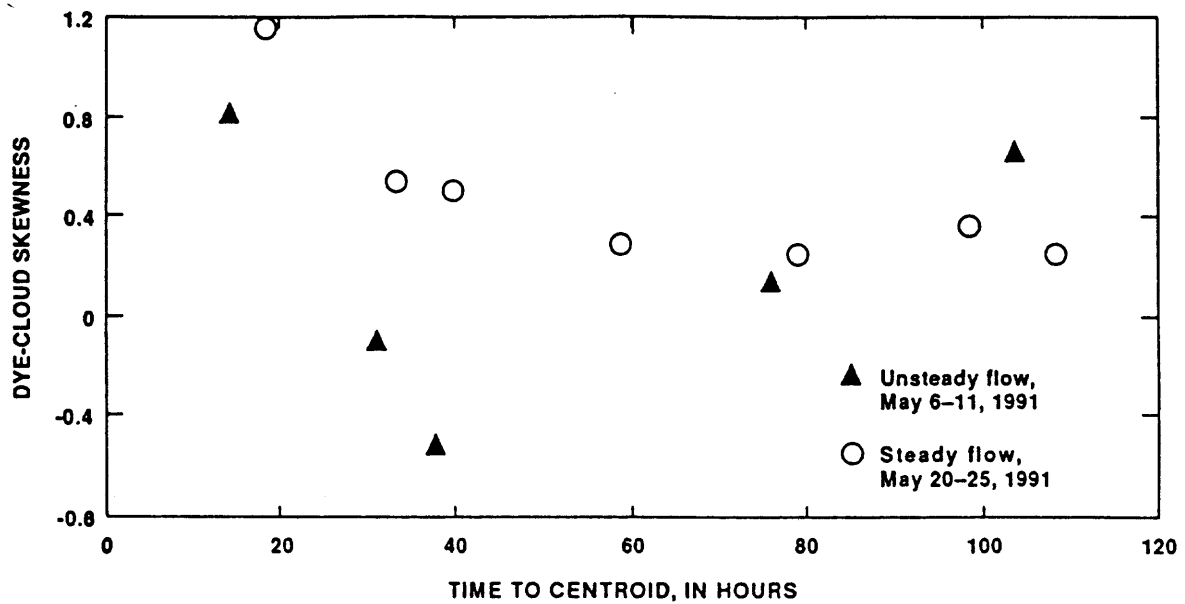
Figure 9.—Relation of dye-cloud skewness to traveltime
of the dye-cloud centroid, Grand Canyon reach.